A Simplified Practical Model for a Walking Beam Type Reheat Furnace with Specific Heat Transfer Characteristics

Lingyan Hu

College of Information Engineering, Dalian University, Dalian 116622, China
E-mail: hulingyan@dlu.edu.cn

Abstract: A simplified technique is introduced to develop a mathematical model according to the specific heat transfer characteristics in a walking beam type reheat furnace. The model can predict the heat flux on a billet surface and temperature distribution inside a billet by the thermal radiation in a furnace chamber. Considering the boundary conditions, the hot gas blackness coefficient is corrected during radiative heat flux calculation which improves model accuracy. The model is simulated with Matlab software. Simulating results verify the effectiveness and feasibility of the proposed modeling method.

Keywords: reheat furnace; radiative heat transfer; thermal model; transient heat conduction equation

1. Introduction

In the metallurgical industry, walking beam type reheat furnaces are one of widely used equipment for slab or billet heat treatment. It’s the typical longitudinal, large furnace which continuously reheat semi-finished billets to a certain temperature which is appropriate for processing in the next rolling mill [1]. The analysis of transient heating characteristics for the billets in this type of furnace has attracted considerable attention during the past several decades since the heat treatment process should reduce energy consumption, pollutant emissions and operating cost. Furthermore, at the furnace exit, requirement of the uniform temperature distribution inside the billet greatly increases the importance of fast and accurate prediction of heat treatment process because this determines the product quality and productivity. Thus models and methodology for investigating the furnace combustion behavior and heat transfer process have very important practical significance to metallurgical engineering systems in steel plants [2].

Up to now, a number of valuable results have been reported and successfully applied in different types of reheat furnaces. The main techniques include the following approaches. The first one solves the full Navier-Stokes and energy conservation equations governing the hot gas flow and combustion process with thermal radiative transport phenomena in a furnace. A few studies have been carried out with CFD simulations [3, 4, 5] where both convection and radiation with fluid flow calculations are considered. Although the sophisticated CFD simulations can be employed to predict the thermal characteristics in a furnace, in practice it fairly costs much due to the large computational time required in order to manage the complexity of the large-scale furnace. The other approach, which is simplified but can reasonably simulate the thermal behavior of billet, focuses on the analysis of radiative heat transfer in the furnace and transient heat conduction inside the billet [1-2,6-15]. In the simplified heat transfer models, only radiation heat transfer in the furnace is considered. The radiation calculations are done using different radiation heat transfer model, for example in literature [1, 6, 7], the temperature distribution inside the slabs is expressed as 1-dimensional model. Other furnace models like [2, 8-10] calculate the temperature distribution in the billets with a 2-dimensional model. In [11-13], the full 3-dimensional temperature model is discussed. However, complex three dimensional transient model makes the problem difficult to analyze accurately and economically in practical application.

It can be seen from the above literature points of view that there are many various models available in the heating process, however every furnace has its own configuration and heat transfer mechanism. There is no uniform model applicable to all kinds of reheat furnaces. Thus, it should be considered to build a specific model aiming at different heat characteristics for different engineering systems. This paper refers to the heat treatment process for copper-alloy billet products in the walking beam furnace. Different from other works, the flat-flame burners are all located on the top of the furnace. The gas flow is small. And this means all heat resource comes from the upside of the billets. And convection flow is not involved in the heat exchange. In terms of the thermal characteristics, we attempt to build a model easily to implement in practical engineering systems. Taking boundary conditions into account, the hot gas blackness coefficient correction is addressed during the modeling.
to make the computation result more precise. At last, the temperature distribution inside a billet is simulated with Matlab software.

2. Configuration of the furnace

Figure 1 illustrates the basic structure of the walking beam reheat furnace considered in the present work. The basic function of reheat furnace is to heat copper billets up to required temperature while maintaining a uniform temperature in the billet with a temperature gradient not greater than 5°C at the exit of the furnace. The requirement of the uniform temperature distribution is to ensure the quality of billets.

The present reheat furnace is divided into three parts: preheating, heating and soaking zones. The total dimensions of the furnace are 6352mm×1600mm×21800mm (Width×Height×Length). There are a number of flat-flame burners located on the top of the furnace. The billets are successively moved into the furnace where fuel-fired burners serve as heat sources. In order to maintain the temperature uniformity in the furnace, the heating zone is divided into two sub-zones and there are eight burners equipped on the top of each zone. Accordingly the soaking zone is divided into eight sub-zones with two or three burners in each zone. The last two sub-zones next to the outlet are regarded as the additional heating zones. There is no burner in the preheating zone. Exhaust gas is re-circulated to preheat billets in this area. Thus billets are mostly heated in the heating and soaking zones. The main role of soaking zone is to reduce the temperature gradient inside a billet.

![Figure 1. Configuration of the beam reheat furnace (mm)](image)

The billet is moved forward by the periodic beam motion. The copper billets mainly have the following two specifications. One type is made of beryllium bronze and the size is 0.33m×0.15m×5.0m (Width×Height×Length). The other type is made of iron bronze and the size is 0.43m×0.21m×5.0m. The billets are assumed to be isothermal of ambient temperature 25°C when moving into the furnace at the inlet. Billet residence time from charging into the furnace to exit is typically 300min to obtain the mean billet temperature of 850°C. The fuel is natural gas with heat value 34.91MJ/ Nm³.

3. Mathematical formulation

3.1 Heat characteristics and assumptions

Intrinsically, the combustion process and hot gas flow within a furnace chamber influence the heat transfer process through conduction, convection and thermal radiation simultaneously. However, in present work, the burners are flat flame and all the burners are located on the top of the reheat furnace. The pulse combustion control technology is applied. Air flow is small inside the furnace. Therefore, it is mostly the upper radiative heat transfer with over 95% proportion of all energy exchange in the furnace. Radiation emitted by hot gas on the upper side of the billet is absorbed. The absorbed radiation is converted into heat energy and it further penetrates inside the billets by means of conduction. By the above analysis of heat characteristics, the following technological specifications and assumptions are given:

(1) Thermal radiation is the only considered mode of heat exchange in the inner heating environment. Other types of heat transfer like convection are negligible. When systems come into stable state, the heat exchange between billets and beams is negligible, as well as the furnace inner walls.
2. For any billet, the temperature of a participating surface is homogeneously distributed inside a billet.
3. The furnace chamber temperature is a continuously piecewise linear function along furnace length. The total heat exchange factor is consistent in the same furnace zone.

3.2 Conductive heat transfer
Conductive heat transfer inside the billet can be normally calculated from the transient three-dimensional heat conduction equation as follows:

$$\rho c_p \frac{dT}{dt} = \frac{\partial}{\partial x} \left( \lambda \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( \lambda \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left( \lambda \frac{\partial T}{\partial z} \right)$$

(1)

where $\rho$, $c_p$, $\lambda$ are density, specific heat, and conductivity of a billet. $T$ denotes the billet current temperature. $x$, $y$, $z$ respectively represent a billet width, length, and height directions. As mentioned in the above sections, there is no burner on the bottom and wall in the furnace. All the flat burners are equipped on the furnace top. Thus the heat energy absorbed by the billets is vertically radiation. Meanwhile basing on the assumptions given in 3.1, the transient model can be simplified into the following one-dimensional heat conduction equation:

$$\rho c_p \frac{dT}{dz} = \frac{\partial}{\partial z} \left( \lambda \frac{\partial T}{\partial z} \right)$$

(2)

Hence

$$\frac{dT}{dt} = \frac{\lambda}{\rho c_p} \frac{\partial^2 T}{\partial z^2} = \sigma \frac{\partial^2 T}{\partial z^2}$$

(3)

The simplification process and conductive heat transfer flow can be illustrated with Figure 2.

![Figure 2. Simplification of heat conduction in a billet](image_url)

where $Billet_j$ denotes the $j$th billet in the furnace, $C_{i,y,z}$ represents the $i$th micro-cell cube inside the billet. $\tau$ is the specific time period for the micro cube to absorb heat energy. Hence, the heat transfer only occurs along billet $z$-axis, namely through thickness or height direction from top to bottom.

By the above heat exchange analysis, it can be found although the model is simplified, its heat transfer much more conforms to the practical heat characteristics. And the temperature transient model is composed by two parts: transient heat conduction equation and boundary conditions.

3.3 Boundary conditions
In this section, the boundary conditions will be analyzed. It’s the essential initial state in order to get the temperature distribution inside the billet. Let $q_u(t), q_l(t)$ be used for the upper and
bottom radiative heat flux on the billet surface in the equation (2). Then the system initial function and boundary conditions are given by

\[
T(z,t) = \varphi(z), \quad 0 < z < H, 0 < t \leq t_0
\]
\[
\lambda \frac{\partial T(z)}{\partial z} \bigg|_{z=0} = q_s(t)
\]
\[
\lambda \frac{\partial T(z)}{\partial z} \bigg|_{z=-h} = q_s(t)
\]

(4)

where \(H\) represents the billet thickness, \(\varphi(z)\) is the initial temperature function along \(z\)-axis. There is no burner on the flank and bottom, all the heat energy comes from the upper side, so \(q_s(t)\) will be negligible. As the thermal radiation mainly comes from the hot gas in a furnace, then the thermal radiation equation is given by

\[
Q_{rg} = \left[ C_0 \cdot \varepsilon_s \cdot \varphi_{gm} \right] \left[ \frac{T_g}{100} - \left( \frac{T_m}{100} \right)^4 \right] \cdot S_n
\]

(5)

where \(Q_{rg}\) is the radiative heat flux, \(T_g, T_m\) represent the gas and billet surface temperatures, \(S_n, \varepsilon_s\) and \(C_0\) are the billet surface heated area, gas blackness and radiation coefficient with \(C_0 = 5.675 \text{ [W} \left( \text{m}^2 \cdot \text{K}^4 \right) \text{]} \) respectively. \(\varphi_{gm}\) is the radiation angle coefficient.

In the heat and soaking zones, the radiation gas is mainly composed by \(CO_2, H_2O\). Because the radiation has strong selectivity, the gas blackness coefficient need correct to get the precise computation. Taking the heat zone I for example, the corrected gas blackness coefficient is given by

\[
\varepsilon_g = \varepsilon_{CO_2} + \varepsilon_{H_2O} - \Delta \varepsilon
\]

(6)

where \(\varepsilon_{CO_2}, \varepsilon_{H_2O}\), \(\Delta \varepsilon\) denote the \(CO_2, H_2O\) blackness coefficient and corrected value of gas blackness. The following procedure is given to calculate \(\varepsilon_g\) in equation (6):

**Step1:** First calculate the average effective ray distance \(L_{heat}\) of heating zone I

According to the furnace configuration, we have

\[
S_{Heat\_top} = W_{inner} \times L_{Heat}
\]

(7)

\[
S_{Heat\_inner} = 2 \times H_{Heat} \times L_{Heat} + 2 \times W_{inner} \times L_{Heat} + S_{Heat\_top}
\]

(8)

where \(L_{Heat}, H_{Heat}, W_{inner}\) represent chamber length, height and inner width of heat zone I. \(S_{Heat\_inner}, S_{Heat\_top}\) are the furnace inner area and furnace top area of heat zone I. The chamber volume \(V_{Heat}\) with hot gas is:

\[
V_{Heat} = W_{inner} \times L_{Heat} \times H_{Heat}
\]

(9)

Then the average effective ray distance \(L_{heat}\) can be calculated by

\[
L_{heat} = \eta \cdot \frac{4 \times V_{Heat}}{S_{Heat\_inner}}
\]

(10)

where \(\eta\) is the gas radiation coefficient, generally taking \(\eta = 0.85 \sim 0.9\).

**Step2:** Calculate the synthetic pressure in furnace

The partial pressure \(P_{CO_2}, P_{H_2O}\) in heat zone I can be obtained through *Combustion technical manual* \cite{14}, then we have

\[
P_{per} = \frac{P_{H_2O}}{P_{H_2O} + P_{CO_2}}
\]

(11)

\[
P_{syn} = (P_{H_2O} + P_{CO_2}) \times L_{heat}
\]

(12)

where \(P_{per}, P_{syn}\) are the partial pressure proportion and synthetic pressure of heating zone I, basing on the above formula, the corrected \(\Delta \varepsilon\) can be inquired, then corrected gas blackness coefficient can be obtained with (6).

The radiation angle coefficient between hot gas and copper billet can be calculated by

\[
\varphi_{gm} = \frac{S_{Heat\_top}}{S_n}
\]

(13)

According to (1)-(7), the heat flux density can be given by
\[ q_s(t) = \frac{Q_{re}}{S_m} = [\varepsilon \cdot C_0 \cdot \varphi_{gm}] \left[ \frac{T_g}{100} - \frac{T_m}{100} \right] \quad (14) \]

If defining a heat transfer coefficient \( C_{(gm)} = \varepsilon \cdot C_0 \cdot \varphi_{gm} \), then

\[ q_s(t) = C_{(gm)} \left[ \frac{T_g}{100} - \frac{T_m}{100} \right] \quad (15) \]

Using the heat flux boundary conditions and heat conduction equation, a temperature distribution inside a billet can be obtained. The discretization process is done using a normal finite volume method which will not be detailed here. In the next section, the simulation for a billet temperature distribution will be discussed.

### 4. Results and analysis

Simulation analysis of a billet in a furnace zone will be discussed with the help of Matlab software. Taking the heating zone I for example, the following parameters and data are collected in the engineering project of Ningxia Beam Reheat Furnace in China:

<table>
<thead>
<tr>
<th>Number</th>
<th>Furnace Parameters</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Flat burner power</td>
<td>230kw</td>
</tr>
<tr>
<td>2</td>
<td>Flat burner number</td>
<td>8</td>
</tr>
<tr>
<td>3</td>
<td>Billet material</td>
<td>C17500</td>
</tr>
<tr>
<td>4</td>
<td>Beam step velocity</td>
<td>0.065m/min</td>
</tr>
<tr>
<td>5</td>
<td>temperature setpoint</td>
<td>850°C</td>
</tr>
<tr>
<td>6</td>
<td>Billet regulation</td>
<td>330(mm)×150(mm)×5000(mm)</td>
</tr>
</tbody>
</table>

According to the *Copper Fabrication Manual* [15], the total heating and holding time for a billet inside a furnace needs at least 300 minutes. The current chamber temperature is 850°C which can be measured by the thermocouples located in the furnace top. The billet surface temperatures can be measured by the contact temperature sensors. And the technical parameters of \( \varepsilon_m, \varepsilon_{CO_2}, \varepsilon_{H_2} \) can be obtained by consulting the *Combustion Technology Manual*. Then furnace gas blackness correction can be calculated as well as \( \varphi_{gm} \) and \( C_{gm} \). The initial temperature inside a billet conforms to the parabolic equation. Use the above thermal model and boundary conditions and program it into M file in Matlab software. Let \( t_0 \) represent the time that a billet stayed in heating zone I. After simulation, we can obtain the following billet temperature distribution pictures:
The simulation calculation begins from the point $t_0 = 30\text{min}$ when a billet is charged into the heating zone I. And the simulation time 30 minutes is taken. From the simulation results on figure 3(a), it can be found that the upper side temperature is greatly higher than the bottom side as the heat transfer radiates from the furnace top. The maximum temperature difference is about 170°C from top to bottom surface. From the picture on figure 3(b), the temperature difference is larger in the middle of a billet than the two end sides. The maximum rising temperature value along a billet height is 45°C during the heating period time.

In order to compare the heating effects when a billet is in different time and positions, the time $t_0 = 50\text{min}$ is the next point to calculate the temperature distribution. The simulation time still keeps 30 minutes. The results are shown in Figure 4.

From the pictures, it can be found that the temperature difference gets smaller inside a billet 20 minutes later in heating zone I. And the temperature rise velocity gets more slowly with a billet staying longer in a furnace. The maximum temperature different is about 140°C from top to bottom. The rising temperature values along a billet height is 15°C during the heating period. For the above simulation process, any point temperature point can be calculated if the billet thickness value and certain time are offered.

5. Conclusions

We have investigated a practical model with specific heat transfer characteristics in a beam reheat furnace. As all the flat flame burners are installed on a furnace top, the thermal radiation is the dominant heat exchange mode in a furnace. This also determines the heat conduction direction from top to bottom inside a copper billet. Basing on these thermal characteristic, the transient conductive equation is simplified into one-dimensional mode. To improve the model accuracy, the hot gas blackness coefficient and radiation angle coefficient are calculated respectively during the calculation of heat flux boundary conditions. The simulation results verify the effectiveness of the proposed approach.

The model can predict the radiative heatflux on a billet surface and the temperature distribution in a billet during a heating process. In the practical engineering systems, only if we know the practical technical parameters of the furnace, the billet temperature distribution and heat flux prediction can be calculated quickly by programmed functions. The modeling methodology can be extended and applied to the similar type of reheat furnace in metallurgy domain.

6. Acknowledgments

This work was supported by the National Science of China (grant no. 61401055), and funding of Liaoning Science Technology Research Program of China (grant no. L2013463).
7. References


